



Dynamic Effects of Diabatization in Distillation Columns

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Presentation Outline

Motivation

Introduction

Methodology

Dynamic Modeling

Simulation Study

Results

Conclusion

Future Work

Motivation

- Increasing focus on environmental issues and resource management
- Distillation is a widely used separation process in the industry, but it is highly energy intensive. Some key numbers for USA in 1988:
 - Distillation accounted for 4% of the total energy consumption ¹
 - Roughly 40% of the processing energy used in refining and continuous chemical processes was used for distillation
- Conventional distillation columns operate at low efficiencies ²
- Diabatic distillation columns **can** provide:
 - Higher efficiencies ³
 - Less utilities and thus less operation cost ⁴

¹ Humphrey, J.L. et al., Separation process technology, McGraw-Hill, 1997

² de Koeijer, G. et al., 2000, Int. J. Applied Thermodynamics 3(3):105–110

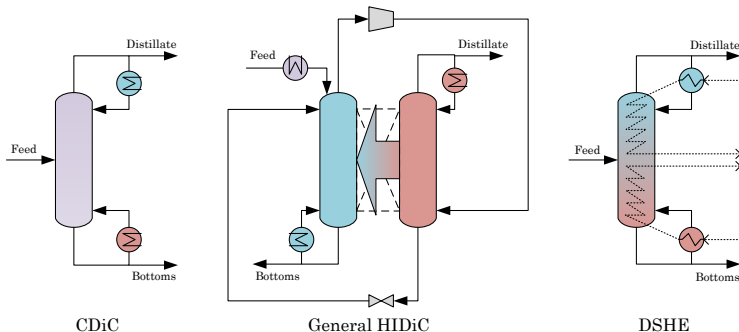
³ Nakaiwa, M. et al., 1998, Appl. Therm. Eng., 18(11), 1077–1087

⁴ Olujic, Z. et al., 2003, J. Chem. Technol. Biotechnol. 78(2-3):241–248

Introduction

(1/3)

- **Adiabatic operation:** Heat is added at the highest temperature (reboiler) and heat is removed at the lowest temperature (condenser), thereby preventing integration (e.g. conventional,...)
- **Diabatic operation:** Heat required to perform the separation is added and/or removed throughout the column (e.g. HIDiC, DSHE, ...)



Introduction

(2/3)

- **Research example:** Verification of high heat transfer performance and enhanced mass transfer performance in a pilot scale (0,8 m diameter) test unit at TU Delft ⁵

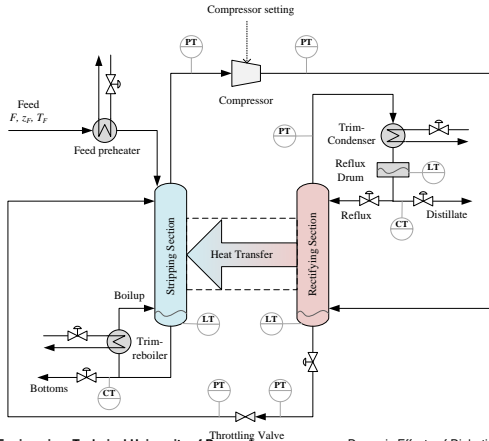


⁵<http://www.ecn.nl>

Introduction

(3/3)

The Heat-Integrated Distillation Column (HIDiC)



CT: Composition Transmitter

LT: Level Transmitter

PT: Pressure Transmitter

Methodology

- Formulate generic, dynamic first-principle model describing:
 - Adiabatic distillation columns (Conventional)
 - Diabatic distillation columns (HIDiC)
- Implement model in simulator (Matlab[®])
- Formulate realistic case-studies and perform numerical simulations
- Dynamic controllability analysis and compare distillation control configurations on decentralized 2×2 system (remaining perfectly controlled)
- Perform closed-loop simulations based on single-loop control strategies

Dynamic Modeling

- Model features:
 - Binary separation of benzene-toluene with **equally sized** rectifying and stripping section
 - **Mass balances**
 - **Energy balances**
 - Liquid tray hydraulics (variable liquid tray holdups)
 - One mathematical term distinguishes configuration (adiabatic, diabatic)
- Major assumptions:
 - Equilibrium stage model
 - Lewis/Randall ideal mixture
 - **Constant pressure** in each section
 - Negligible vapor holdup compared to liquid holdup
 - Negligible changes in sensible heat
 - Homogeneous stages (ideally mixed)

Simulation Study

- Considered distillation column configurations:
 - Conventional distillation column (CDiC)
 - Heat-Integrated Distillation Column (HIDiC)

Selected model parameters:

Parameter	Value
Top purity	99% benzene
Bottom purity	95% toluene
Number of stages	20
Feed stage location	11
Feed flow	$100 \frac{\text{kmol}}{\text{h}}$
Feed benzene content	0.50
Stripping section pressure	0.1013 MPa
Hydraulic time constant	0.0042 h
Heat of vaporization	$30,001.1 \frac{\text{kJ}}{\text{kmol}}$
Relative volatility	2.317
Heat transfer rate	$9,803 \frac{\text{kJ}}{\text{h} \cdot \text{K}}$

Results - Open-loop

(1/2)

Dynamic responses to step-changes in disturbance variables.

Black curves: +5%

Gray curves: -5%

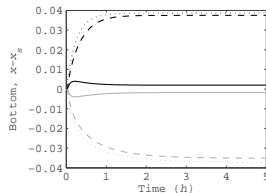
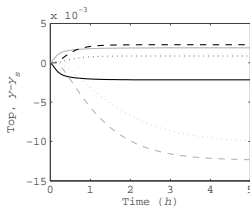
Legends:

Dashed lines: HIDIc

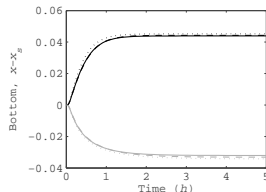
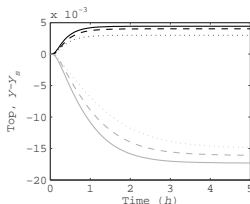
Dotted lines: CDiC

(Solid lines: HIDIc without condenser and reboiler)

Feed flow rate

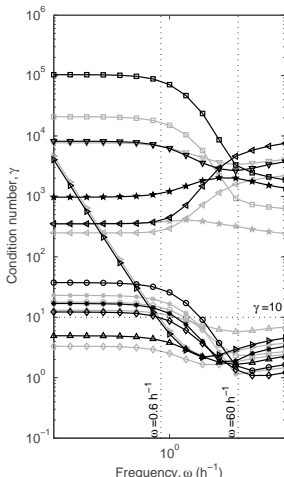
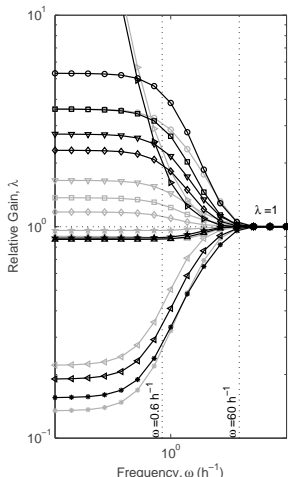


Feed composition



Results - Open-loop

(2/2)



Controllability Analysis
Dynamic RGA Analysis and
SVA applied on a
decentralized 2×2 :
HIDiC (black lines)
and a
CDiC (gray lines).

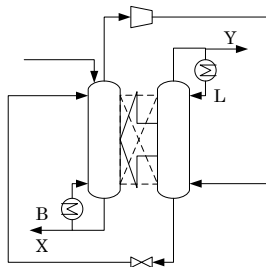
Legends:

- (○): LV
- (*) : DV
- (□): $(L/D)V$
- (△): LB ←
- (▽): $L(V/B)$
- (▷): DB
- (◁): $D(V/B)$
- (*) : $(L/D)B$
- (◇): $(L/D)(V/B)$

Results - Closed-loop

(1/2)

- SISO controller based on an approximated First-order-Plus-Time-Delay model

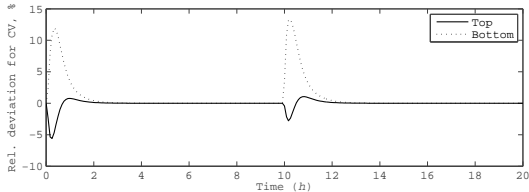


- Transfer function:

$$\begin{bmatrix} dY \\ dX \end{bmatrix} = \begin{bmatrix} \frac{-0.04972}{0.1336s + 1} & \frac{-0.2566}{0.5070s + 1} e^{-0.0545s} \\ \frac{-0.009427}{0.055465s + 1} e^{-0.0897s} & \frac{0.3144}{0.4357s + 1} \end{bmatrix} \begin{bmatrix} dL \\ dB \end{bmatrix}$$

Results - Closed-loop

(2/2)



Closed-loop responses for the

HIDiC to:

$t = 0$ h: +10% step-change in
feed flow rate

$t = 15$ h: -10% step-change in
feed composition

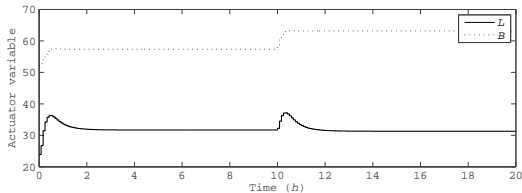
Tuning parameters (From S-IMC):

$dL \rightarrow dY_D$:

$K_c = -0.0790$, $\tau_I = 0.5158$ h

$dB \rightarrow X_B$:

$K_c = 8.3147$, $\tau_I = 0.4357$ h



Conclusion

- A flexible and generic model have been developed to describe various diabatic distillation column configurations
- Various feasible pairings exist for the HIDiC
- Diabatization causes increased coupling between input-output variables
- In this study, among others an *LB*-structure seemed to be a promising control structure for a HIDiC

Future Work

- PhD Project initiated with the title **Operation and Design of Diabatic Distillation Processes**
- Develop detailed model framework for adiabatic and diabatic distillation processes
- Investigations, including:
 - Thermodynamics: Impact on complex thermodynamic modeling on e.g. dynamics
 - Operability: Abnormal operation, e.g. steady-state multiplicity
 - Control: Development of regulatory and multivariable control strategies

End

Thank you for your attention